Knee Joint Kinematics Measured Using Simultaneous Video Motion Capture and Fluoroscopy

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Introduction: Musculoskeletal models improve our understanding of biomechanical factors affecting knee joint degeneration and total knee replacement (TKR) performance. Such models typically simulate knee joint motions during gait or closed-chain knee extension, but many have limited predictive capabilities for simulating other demanding activities (e.g. rising from a chair or squatting). Comprehensive descriptions of joint dynamics during such activities are scarce (Banks 2000), resulting in a lack of input data for continued model refinements.

Inputs loads and kinematics for musculoskeletal models are typically calculated from in vivo subject data derived from external tibial and femoral limb segments’ motion acquired by video motion capture or internal tibial-femoral motions acquired by radiographic imaging. Computational models are sensitive to small deviations in knee kinematics (Fregly 2008) and differences can arise between inputs acquired from these two methods. However, it is unknown whether differences in external limb motions correspond to differences in internal tibial-femoral motions, and their relationship is not well understood.

This study compares external and internal knee joint kinematics measured simultaneously in vivo using video motion capture and fluoroscopy during chair rise/sit and squatting activities in subjects with fixed bearing and mobile bearing TKR. The objective was to understand the magnitude of variation existing in the in vivo measurements and its potential impact on input parameters for musculoskeletal models.

Methods: Three female (6 TKR) and 4 male (4 TKR) subjects provided written informed consent to participate in this IRB approved study. Subject age, weight and BMI averaged 68±8 years, 79±17 kg and 28±4 respectively. Subjects were implanted with one of two types of TKR (PFC Sigma, DePuy Orthopaedics, Inc., Warsaw, IN), including cruciate retaining fixed bearing (FB-CR) and rotating bearing (RB-CR) designs, an average of 7±3 years prior to participation. Clinical outcomes were evaluated using the Knee Society Score (KSS) and passive range of motion was measured with a goniometer. Limb and prosthesis alignment were measured from digitized clinical radiographs.

Subjects were instrumented with reflective markers to define anatomic joint centers and redundant markers about the pelvis and lower limbs. Each subject performed chair rise/sit from an armless stool (height adjusted to 80% of tibial length) and double leg squat down/up activities in a controlled manner. Knee motions during each activity were recorded simultaneously using a 10 camera video motion capture system (Vicon MX, Vicon Corp., Los Angeles, CA) recording at 100 Hz. and a fluoroscopy c-arm imaging system (OEC 9400, OEC Medical Systems Inc., Salt Lake City, Utah) recording at 30 Hz.

Three-dimensional external and internal knee joint kinematics in the sagittal, frontal, and horizontal planes were computed for each system. Video motion capture data were analyzed using commercial software (Vicon Corp.). External knee kinematics in that system (Ext Kin) were calculated as the motion of the tibial and femoral limb segments. Fluoroscopic images were analyzed using published methods (Banks 1996) to match the 3-D prosthesis CAD geometry to the 2-D images. Internal knee kinematics in that system (Int Kin) were calculated as the relative positions of the femoral and tibial components. Ext Kin and Int Kin were compared by synchronizing the data in time and correcting for different recording frequencies. The absolute variations in knee kinematics (Kin_Variation) were calculated at 0.1 second intervals using the following equation: Kin_Variation = | Ext Kin − Int Kin |, then averaged over the entire range of motion for each activity.

Results: Pain and function outcomes were excellent, with KSS ≥90 in all subjects. Maximum passive knee flexion averaged 109°±8° (range, 97° to 128°). Post-operative frontal plane limb alignment averaged 173°±3°. Maximum knee flexion during the chair and squat activity averaged 102°±8° and 105°±11°, respectively.

During the chair stand/sit activity and the chair up/down activities, tibial internal rotation with knee flexion was observed with both methodologies. Considerable variations between Ext Kin and Int Kin were noted for both TKR designs during each activity. During the chair rise/sit activity (Figure 1 - Chair), Kin_Variation was greatest for motion occurring in the frontal plane (ab/adduction) of fixed-bearing TKR and in the horizontal plane (int/external rotation) for rotating-bearing TKR. During the squat activity (Figure 1 - Squat), Kin_Variation was greatest for motion occurring in the sagittal plane (flexion-extension) of fixed-bearing TKR and in the horizontal plane (int/external rotation) for rotating-bearing TKR. Kin_Variation had the smallest magnitude for both activities in both TKR groups when the knee was near full extension (0°-40°) compared to mid-flexion (40°-80°) and high-flexion (90°-120°) ranges. In general, frontal plane motion (ab/adduction) was consistently greater for Ext Kin measured using motion capture compared to Int Kin measured using fluoroscopy. In contrast, sagittal plane motion (flexion-extension) was typically greatest for Int Kin.

Discussion: Simultaneous in vivo measurement external limb motions and internal tibial-femoral motions during these high flexion activities was technically challenging. Marker occlusion due to positioning of the patient and fluoroscopy system within the motion capture field occurred frequently, necessitating the redundant markers.

When using skin-based markers, the robustness of the joint center calculation must be increased to account for extraneous external motion. Many built-in commercial algorithms rely on simple methods for determining joint center that leave little room for noisy marker motion. Particularly, the knee joint center is very sensitive to marker placement and high flexion movements. Specialized musculoskeletal models have been developed to successfully predict dynamic femoral-tibial contact forces, pressures and wear that occur with in vivo TKR function (Fregly 2002; Fregly 2005; Zhao 2007). However, few studies have included simultaneous capture of external joint dynamics and internal knee kinematics in the same patient populations, (Zhao 2007; Banks 2000)

To reduce the experimental error using standard algorithms, it is important to use supplemental markers to more accurately calculate joint centers during movements prone to noise and during times of high marker occlusion. With proper measures, the offset between video and radiographic measurements can be identified repeatably.

Direct comparison of the knee kinematics measured using video motion capture and the implant kinematics measured using fluoroscopic imaging can reflect differences in the measurement techniques. Specifically, motion capture uses skin-based markers to distinguish the joint centers along the entire limb (hip, knee, and ankle), generating limb axes based on marker position and then computing motion in all planes. Offset between these limb axes and the axes of the tibial and femoral components will contribute to observable difference in kinematics. In the current study, the magnitude of knee abduction measured with the video motion capture system exceeded the implant abduction measured with fluoroscopy – likely due to kinematic cross-talk from inexact alignment of the knee flexion/extension axis as defined by the motion capture markers.

References

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